Investigations of Long-range and Short-range Wakefield Effects on Beam Dynamics in TESLA-type Superconducting Cavities (LRW/SRW)

(10-07-20 Version for Run 3 Studies)

PERSONNEL

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FNAL Collaborators: Dean Edstrom, engineering physicist, laser specialist, and FAST operator; Peter Prieto, engineer, HOM detector designer and commissioner; Jinhao Ruan, physicist, laser specialist, and qualified FAST operator; Randy Thurman-Keup (FNAL), physicist, diagnostics guru.

PURPOSE AND METHODS

• *Background information:* The LCLS-II accelerator will be a continuous wave superconducting linac based on TESLA-type cavities and cryomodules [1]. Off-axis steering in these cavities may cause emittance dilution due to transverse wakefield effects. This will be particularly critical for the injector where beam will enter the first cryomodule at <1 MeV and be at no more than 9 MeV for the first three cavities [1]. A schematic of the LCLS-II injector is shown in Fig. 1. The transverse kick angles go inversely with energy and directly with offset and charge. These effects can be investigated at the FAST facility with its unique configuration of a PC rf gun, two TESLA single cavities in series, and then a cryomodule. Previous FAST studies were on the observation of sub-macropulse beam centroid oscillations at near-resonant conditions [2] and on the first detection of head-tail kicks due to short-range wakefields in CC1 and CC2 [3-5]. The latter emittance dilution effects in the first tests in Runs 1,2 were found to be larger than the long-range effects and are very relevant to the LCLS-II injector commissioning. Due to the very tight schedule of LCLS-II injector commissioning in 2021, it is very important to test the beam-steering methods based on HOM signals in TESLA-type cavities, including a cryomodule. *See Addendum for SLAC objectives for Run 3.* (SRW effects studies in CM2 using the streak camera were postponed to Run-4 consideration.)

• *Scientific or technical motivation and purpose:* Generation and preservation of low-emittance beams are ongoing challenges for the accelerator community. Off-axis transport of beams in the accelerator cavities can cause long-range (LRW) and short-range wakefields (SRW) with concomitant effects on transverse electron beam dynamics and emittance dilution. This happens on both the sub-macropulse and sub-micropulse time scales due to the LRW and SRW, respectively.

• *Experimental methods:*

1.We first plan to establish the corrector settings that minimize the four HOM detector signals in CC1 and CC2 at the same time as a reference point. We will check for any sensitivity of the reference point to bunch charge.

2. Then, we propose generating long-range wakefields and short-range wakefields in TESLA-type superconducting rf cavities by steering the beam off-axis with the corrector magnets located before CC1, CC2, and CM2. The four existing higher-order-mode (HOM) detectors monitor the dipolar modes in the first two passbands from 1.6-1.9 GHz in the first two cavities. The SLAC prototype HOM boxes will be commissioned with beam. We plan to utilize a beam-offset monitor (BOM) based on the HOM signals and the correlated beam positions.

3. The head-tail kicks within a micropulse due to off-axis steering will be evaluated with the downstream X121 OTR screen and the synchroscan streak camera. The bunch-by-bunch rf BPMS will be utilized as warranted for LRW/HOM effects.

• *Expected results*: We expect to develop the BOM capabilities based on these HOM tests. These tests can be used to optimize the FAST linac setup, and they have already informed the LCLS-II designs of their HOM detectors for their first cryomodule (and linac). The *objective is to mitigate emittance dilution* due to off-axis beam transport by minimizing the dipolar HOMs. We will test steering protocols in CM2 using the SLAC prototype HOM boxes that would apply to LCLS-II CM01. The LCLS-II team also has an interest in using the BOM aspect to give an early warning on potential beam loss conditions in the CMs. In addition, we would obtain a data base for training a possible machine learning (ML) application for minimization of HOM dipolar signals for the FAST setup and then the LCLS-II injector and linac. For the short-range effects, we would extend our streak camera image data base from Runs 1,2 by steering from a reproducible reference at lower energy in support of a journal article submission. The results will be compared to ASTRA simulations to benchmark it and prepare for application to LCLS-II.

BEAM CONDITIONS-1

The initial series of LRW/SRW experiments in Run 3 will be performed using the FAST/IOTA injector with beam sent to the LE dump when not in use with a screen. The main goals are: 1) Commissioning of the SLAC prototype HOM detector boxes and the two new FNAL boxes at 41 MeV as available. 2) evaluation of the LRW and SRW effects in the single capture cavities denoted as CC1 and CC2 under controlled beam-steering and setup conditions at 20.5, 12.5 MeV, and 10.5 MeV (obtained by reducing the Gun energy from 4.5 MeV to ~2.5 MeV; 3) observation of the resulting electron-beam dynamics in the BPM data and streak camera images as guided by the HOM values at 20.5,12.5 MeV, and 10.5 MeV. Six shifts are described later.

Beam species: electrons

Intensity: 100-1500 pC/b, 500 pC/b reference

Energy: ~41 MeV initially at exit of CC2 *assuming this is nominal*: Then 20.5, 12.5, and 10.5 MeV total energy setups requested: first with 8 and 8 MV/m in CC1 and CC2 (if CC2 is operational, otherwise use 16 MV/m in CC1), respectively, then 8 and 0 MV/m. *The latter mimics the SLAC gradient plan in first two cavities of their cryomodule-01. A reduced gun energy of ~2.5 MeV is used to approach the LCLS-II injector energy.*

Number of bunches: 1-150 depending on charge

Micropulse repetition Freq.: 3 MHz.

Transverse emittance: 2-3 mm mrad normalized, depending on charge

Bunch length: 4-15 ps, uncompressed

Momentum spread: nominal at 0.1%

Orbit modifications: Yes, steering will be done at H/V100, H/V101, and H/V103 to minimize HOMs. Then beam steering will be done with these to induce HOMs and SRWs. These upstream steerings can be compensated with the H/V104, H/V106, and H/V111 correctors and others to maintain transport to the LE dump or X107 and X121 or other as needed. See Fig. 2 for the locations of the correctors and other diagnostics at FAST. Initial corrector value changes will be done with only a few bunches until efficient transport to the low energy beam dump is established.

Laser Spot size: Nominal 0.5 mm rms in x and y as in February 2020 or new nominal, but plan to scan size only with iris change as allowed.

Solenoids: Nominal settings for zero field at the cathode, but we may scan them to change beam size at 9-way, CC1,CC2, and X107.

Stability: Need standard laser and electron beam stability for position, size, angle, divergence, phase, energy, and energy spread. We expect the shot-to-shot jitter to be <10 % of the parameter value and <0.1 of the energy.

BEAM CONDITIONS-2

The second series of experiments proposed in Run 3 will be performed using the FAST/IOTA injector with beam sent through CM2 to the HE beam dump when not in use with a screen. The main goals are: 1) evaluation of the LRW effects in the capture cavities denoted as C1-C8 under controlled beam-steering and setup conditions at 100 MeV 2) observations of the resulting electron-beam dynamics in the BPM data and X455 camera images as guided by the HOM values at 100 MeV, and 3) Commissioning and operation of the SLAC prototype HOM detector boxes and the new FNAL HOM boxes on CM2 at 100 MeV. Shifts 7-12 are described later.

Beam species: electrons

Intensity: 100-1500 pC/b, 500 pC/b reference

Energy: 41 MeV at entrance to CM2 and ~100 MeV initially at exit of CM2 *assuming this is nominal:* Then mimic the SLAC gradient plan in the 8 cavities of their injector cryomodule (8,0,0, 16,16,16,16,16) with 12.5 MeV input for 100 MeV total. Other input energy options to be developed after initial run experience.

Number of bunches: 1-150 depending on charge

Micropulse repetition Freq.: 3 MHz.

Transverse emittance: 2-3 mm mrad normalized, depending on charge

Bunch length: 4-15 ps, uncompressed

Momentum spread: nominal at 0.1%

Orbit modifications: Yes, steering will be done at H/V125 to minimize HOMs in CM2. Then beam steering will be done with these to induce HOMs and SRWs. These upstream steerings can be compensated with the H/V44x and H/V45x correctors and others to maintain transport to the HE beam dump or X455 or other as needed. See Fig. 3 for the location of the station and other components at FAST. Initial corrector

value changes will be done with only a few bunches until efficient transport to the high energy beam dump is established.

Laser Spot size: Nominal 0.5 mm rms in x and y as in February 2020 or new nominal, but plan to scan size only with iris change as allowed.

Solenoids: Nominal settings for zero field at the cathode, but we may scan them to change beam size at 9-way, CC1,CC2, and X107.

Stability: Need standard laser and electron beam stability for position, size, angle, divergence, phase, energy, and energy spread. We expect the shot-to-shot jitter to be <10 % of the parameter value and <0.1 of the energy.

APPARATUS

•Sketch of the layout with equipment and dimensions: HOM detector boxes are in the racks near CC1 and CC2. X121 Streak camera in optical hut. See Fig. 2. For Run 3, SLAC will provide the necessary hardware and software for their prototype HOM detectors on TESLA-type cavities. FNAL digitizer channels and ACNET may initially be used. After initial commissioning, the SLAC boxes (8 dipole ch) will be moved to CM2 HOM signal access at rack 219 where two 12-channel digitizers exist with links to ACNET. Two new FNAL HOM multimode boxes will also be used there to supplement these as available.

•Engineering and technical personnel support: Need FAST machine operators

•Infrastructure needs: rigging, vacuum, clean rooms, cooling, gas lines, cryogenics (NA)

•Instrumentation and detectors: The experiments will rely on all existing diagnostics of the FAST injector linac with particular emphasis on the HOM detectors for CC1 and CC2, SLAC prototype detectors, the bunch by bunch rf BPMs in the whole beamline, X121 streak camera, charge monitors, virtual cathode camera images, and imaging stations.

•Electronics and data acquisition: power supplies, cables, oscilloscopes, digitizers, controls: We need the existing spare digitizer channels in the crates in Racks 243, 245, and 219 respectively, for the CC1 and CC2 upgraded detector boxes with mode 30 or quadrupole mode channels functional in ACNET and the SLAC prototype boxes.

•Computing: front-end computers, networking, data storage, data backup, off-line analysis. Standard needs for a run. Programs used before from Chip, Jinhao, and Randy for HOM, rf BPMs, etc. data acquisition and MATLAB-based image acquisition will need some minor revisions. Need extensions to the high energy beamline. Off-line analysis with ImageTool. Data also will be backed up in Redmine Files. https://cdcvs.fnal.gov/redmine/projects/lrwsrw/wiki

RUN PLAN

•Proposed installation plan: When ordered parts become available, two new HOM detector chassis will be augmented with mode 30 channels in parallel to the dipolar mode channels. Detectors are installed at this time with dipolar mode channels for passbands 1 and 2 only.

   The LCLS-II prototype detectors have been prepared for Run 3 and will be installed in an appropriate rack. We would start with CC1 and CC2 tests in Racks 243 and 245, then rack 219 for CM2. At some point in Run 3, combining detector boxes with 10 to 12 channels for CM2 dipolar HOMs would be critical to implement and evaluate in collaboration with Dan Broemmelsiek, should he have interest.

•Requested running period and approximate duration: 12 shifts in Run 3.

•Preferred shift duration and distribution in time: <u>COVID-19 constraints may restrict travel so virtual attendance for SLAC staff is first option, and Chip's, Randy's, Brian F.'s, Peter's, and Jinhao's schedules are key.</u> We propose ~8-hr shifts, 2 days in a work week with lead time provided for arranging schedules. Suggest 1600-2400 CDT with option to extend longer while tunnel work continues on day shift in October. Studies beginning in October as estimate if available. Depending on the prognosis for the CC2 tuner, we may start with the SLAC HOM chassis commissioning which are both in hand for final checkout at FNAL. Preferably, one preliminary CC1, CC2 HOM detector commissioning shift (4-6 hrs) with Brian, Randy, Alex (virtual), and operator should be done before any such full shifts in Run 3. Shifts with corrector programs, any laser spot changes, and streak camera would benefit from D. Edstrom and/or J. Ruan as operators particularly. Currently, Chip, Jinhao, Brian, Peter, and Randy have site access as I understand it.

Shifts 1,2: E_{tot} = 41 MeV or nominal for Run 3; SLAC HOM boxes: Establish reference steering to minimize dipole HOMs at 500 pC/b, 50 b. Scan correctors H/V101, HV103 from reference in 0.25-A steps from -1.0 to 0 to +1.0 A at 101, while recording HOMS (dipolar) and rf BPMs. Use H/V 104, HV106, H/V 111 to

compensate trajectory. Laser spot at 0.5 mm, 50 b. *Test SLAC prototype boxes (8 channels in hand)* and two new FNAL boxes (4 ch, multi-mode) as available. Beam in LE dump. These should be day shifts to match Brian Fellenz's schedule in October, although OSC tunnel work may be ongoing to work around.

Shifts 3,4: E_{tot} =20.5 MeV: Work our way down from 41 MeV or new normal, and check steering, data acquisition, and BPM effects as we go (per Jinhao). Establish reference steering to minimize dipole HOMs at 500pC/b, 50 b, 20.5 MeV. Scan correctors H/V101, H/V103 from reference in 0.25-A steps from -1.0 to 0 to +1.0 A for both locations, while recording HOMS (dipolar) and rf BPMs. Use H/V 104, HV106, and/or H/V 111 to compensate trajectory. Laser spot at 0.5 mm, 50 b. Recommission the transport to X121 and streak camera operations for short-range wakes under reference steering conditions and laser spot size. Develop set of corrector values to keep trajectory to X121 using Jinhao's linear optics model after steering before CC1 or CC2. Centroid oscillations and SRW kicks should be 2x bigger than in Run 2 for CC2 if CC2 is on. Continue sets of streak camera evaluations of SRW for stepped, off-axis steering in CC1 and CC2 from a reliable reference steering point with minimal dipolar HOMs. 500 pC/b, 50 b, Save 20+ streak images each setup. Vary charge: 100, 250, 1000, 1500 pC/b.

Shifts 5,6: E_{tot}= 12.5 and 10.5 MeV: Establish reference steering to minimize dipole HOMs at 500 pC/b, 50 b. Scan correctors H/V101, H/V103 from reference in 0.25-A steps from -1.0 to 0 to +1.0 A at 101, while recording HOMS (dipolar) and rf BPMs. Use H/V 104, HV106, H/V 111 to compensate trajectory. Laser spot at 0.5 mm, 50 b. Recommission the transport to X121 and streak camera operations for short range wakes under reference steering conditions and laser spot size. Develop set of corrector values to keep trajectory to X121 after steering before CC1 or CC2. Kicks and centroid oscillations should be 3x bigger than in Run 2 for CC2. Continue sets of streak camera evaluations of SRW for stepped, off-axis steering in CC1 and CC2 from a reliable reference steering point with minimal dipolar HOMs. 500 pC/b, 50 b, Save 20+ streak images each setup. Vary charge, 100, 250, 1000, 1500 pC/b. Reduce gun energy to ~ 2.5 MeV and take LRW/SRW data at 10.5 MeV.

Shifts 7-10: E_{tot} = 100 MeV: Use the nominal setup for IOTA except HOMs would be minimized in CC1 and CC2. Setup beam to high energy dump with a few bunches at 500 pC/b in first shift. With *SLAC HOM boxes installed for CM2 signals*, record the as-found signals with 50 b for the 8 upstream channels and then the 8 downstream channels. In parallel use the two new multi-mode HOM boxes to look at the C1,2

and C7,8 available channels. Use H/V 125 to minimize HOMs in CM2. Then scan around reference by 0-3 mrad horizontally and vertically, subject to beam transport. Record all rf BPM array data including 8 downstream in the high energy line distributed over 80 m using 100-shot averages nominally. Vary charges of 0.25, 1.0, 1.5 nC. Possible A. Edelen ML data and J. Sikora data requests may be in parallel. Measure emittance before CM2 (X121) and after CM2 (X455) as found and with HOMs minimized. If time, with a target of 12.5 MeV established in shift 5, transport beam into CM2 with SLAC CM01 gradient pattern for ~100 MeV out, take corrector and rf BPM data sets with this lower energy injection.

Shifts 11,12: E_{tot} ~<100 MeV: Contingency for CM2 studies with possible Auralee ML data and J. Sikora data requests in dedicated shifts. For instance, can ML methods quickly determine which cavities have the most detrimental off-axis mode coupling and thus help guide HOM signal limits in feedbacks? Alternate: establish setup to HE beam dump with lower input energy and CM2 in SLAC CM01 setup. HOMs minimized in CC1, CC2, and CM2.

• Proposed decommissioning plan: NA for Run 3.

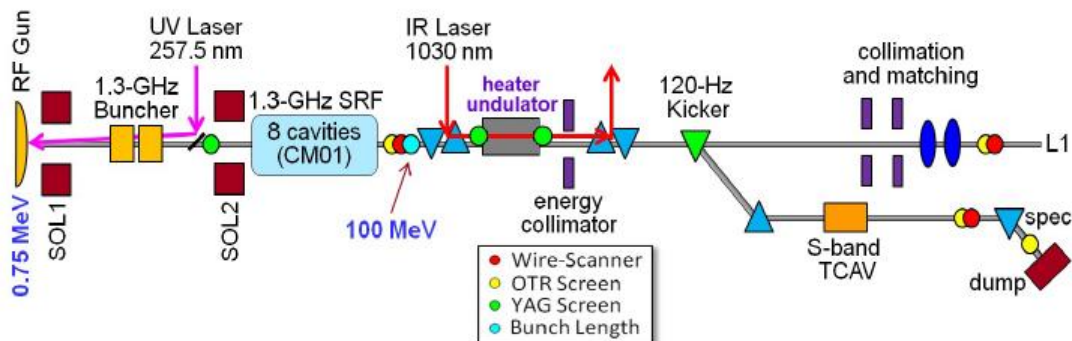**FUNDING**

Background documentation:

Fig, 1. Schematic of the LCLS-II injector showing the rf Gun, buncher, cryomodule 01 (CM01), laser heater, and downstream diagnostics [1].
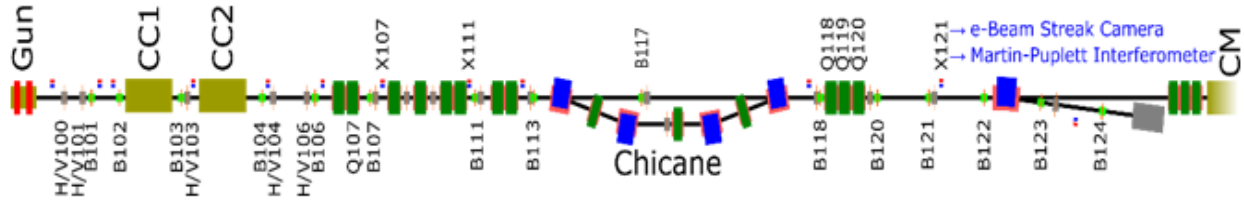
Fig. 2. Schematic of the FAST injector linac showing the gun, CC1, CC2 , and locations of correctors, rf BPMs, and imaging screens (X107, X121) [2].
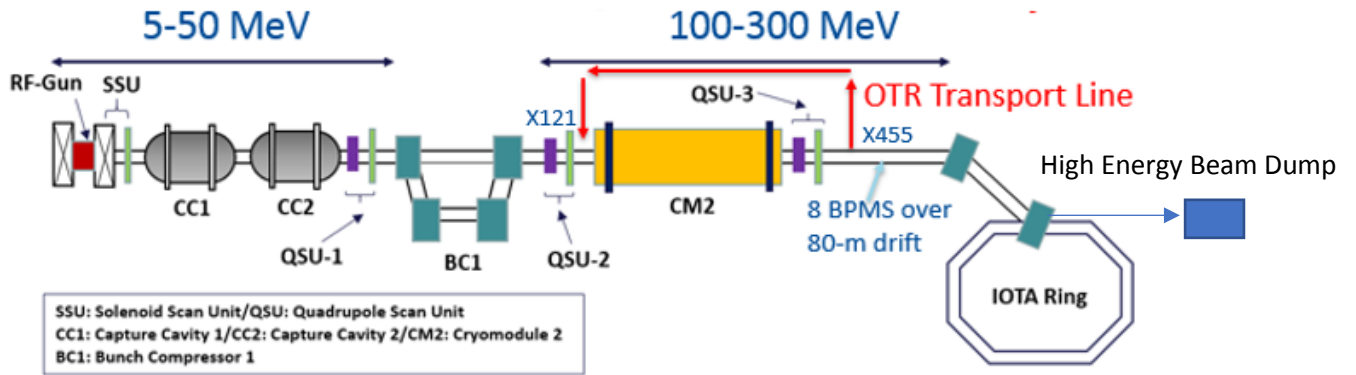

Fig. 3. Schematic of the FAST/IOTA injector and high-energy beamline with CM2, X455, and High energy beam dump.

[1] F. Zhou *et al.*, "LCLS-II Injector Physics Design and Beam Tuning", Proc. of IPAC17, TUPAB138, www.JACoW.org.

[2] A.H. Lumpkin et al., "Submacropulse electron-beam dynamics correlated with higher-order modes in TESLA-type superconducting rf cavities", Phys. Rev. Accel. and Beams, **21**, 064401 (2018).

[3] A.H. Lumpkin et al., "Observations of Short-Range Wakefield Effects in TESLA-type Superconducting rf Cavities", WEP042, Proc. of FEL19, Aug. 26-30, 2019, Hamburg, Germany, www.JACoW.org.

[4] A.H. Lumpkin et al., "Submicropulse electron-beam dynamics correlated with short-range wakefields in TESLA-type superconducting rf cavities", Phys. Rev. Accel. and Beams, **23,** 054401 (2020).

[5] A. H. Lumpkin, R. Thurman-Keup, D. Edstrom Jr., P. Prieto, J. Ruan, B. Jacobson, A. Edelen, J. Diaz-Cruz, F. Zhou, "Direct Observations of Submicropulse Electron-Beam Effects from Short-Range Wakefields in TESLA-type Superconducting rf Cavities", submitted to IBIC 2020 Proceedings (Sept. 2020).

Addendum to FAST Run 3 Proposal: "Investigations of Long-range and Short-range Wakefield Effects on Beam Dynamics in TESLA-type Superconducting Cavities (LRW/SRW)"

Co-PI's: Bryce Jacobson (SLAC) and Alex Lumpkin (FNAL)

Objectives Relative to LCLS-II injector:

1) Verify operation of each SLAC HOM detector chassis and calibrate with beam using "standard" FAST CC1/2 configuration and benchmark against past LRW/SRW measurements using Fermilab HOM detector modules.
2) Replicate as closely as possible LCLS-II injector cavity energy profile and study short- and long-range wake field effects at lower energy. CC1/2 energy goal is CC1 @ 8 MeV, CC2 @ 0 MeV. Gun energy goal is as low as operationally tolerable 2.5 ~ 3 MeV. This low energy (~10.5 MeV) beam would be transported to the low-energy absorber.
3) Instrument CM2 with SLAC HOM detectors (8 channels), minimize signals by steering and correlate offsets from reference with any LRW trajectory oscillations. This can be done using "standard" CM2 injection energy or using the low-energy beam from objective (2).
4) Cross check all results with simulations (SLAC effort) using FAST beamline model.

Completing the above objectives would greatly inform the LCLS-II project as these HOM detectors are expected to be critical for commissioning, and this collaboration has high-impact to DOE goals. Confidence is gained by validating the newly-built SLAC HOM detector hardware, which while based on the Fermilab design, also includes programmable amplifiers and attenuators for the ranges of low charge operation expected of the LCLS-II injector. The results of the low-energy CC1/2 configuration studies provide insight to the beam dynamics in the first cavities of the LCLS-II injector related to wakefield-induced head-tail kicks and emittance growth. Experience with an instrumented cryomodule and correlation with LRW oscillations is also beneficial for the program, especially as this data may serve as a training set for machine learning (ML) tactics. For instance, can ML methods quickly determine which cavities have the most detrimental off-axis mode coupling and thus help guide HOM signal limits in feedbacks? Confirming that simulated and experimental data from FAST agree implies that modeling efforts for the LCLS-II setup can be trusted in the future.

Note on beam charge:

While LCLS-II will operate between 50 – 300 pC, so looking at lower charges than typical at FAST is fine. Our detector modules will detect these low charges based on our work in Run 2. However, the amount of OTR light (especially at low energies) coupled into the streak camera and number of shots to integrate to obtain statistically worthwhile images is a limiting factor.